HUMAN VACCINES & IMMUNOTHERAPEUTICS
2023, VOL. 19, NO. 2, 2256041
https://doi.org/10.1080/21645515.2023.2256041

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

The impact of collective action dilemma on vaccine hesitancy: Evidence from China

Yiqing Su, Xiaoting Zhang, and Shifei Zhang

School of Public Policy and Management, Guangxi University, Nanning, China

ABSTRACT
Vaccine hesitancy has dramatically decreased the speed of vaccination and stalled global health development. While the factors influencing vaccine hesitancy and mitigation measures have been explored in depth by existing studies, research from the perspective of human interaction is lacking. Based on the theory of collective action, this paper analyzes how free riding behavior affects vaccine hesitancy and how the vaccine hesitancy caused by free riding behavior can be solved. Using 2,203 survey data sets from China, this paper examines the influence of the collective action dilemma – represented by free riding behavior – on COVID-19 vaccine hesitancy. The empirical results show that the existence of free riding behavior is an essential cause of vaccine hesitancy. Based on this conclusion, this paper discusses how to further alleviate the problem of vaccine hesitancy caused by collective action dilemmas by promoting cooperation. The findings of this paper may be helpful to promote various types of vaccines and further suggest that countries should assume the perspective of solving the collective action dilemma to achieve increased vaccination rates.

ARTICLE HISTORY
Received 31 May 2023
Revised 11 August 2023
Accepted 1 September 2023

KEYWORDS
Vaccine hesitation; free riding behavior; collective action logic; governance; China

Introduction

Vaccination programs can contain epidemics of devastating diseases and save millions of lives each year, thus providing enormous benefits for individuals and societies.[1,2] For many diseases, the success of vaccination plans depends on public acceptance of vaccination. Although vaccination has proved to be very effective in reducing the mortality and incidence rate of many infectious diseases, fears associated with undermined public trust and acceptance of vaccines continue. In certain regions of developed countries, outbreaks of various epidemics, including measles, polio, diphtheria, and pertussis, are mainly related to unvaccinated individuals or communities.[3–6]

Vaccine hesitancy undermines vaccination coverage worldwide and delays the formation of herd immunity.[7] The prevalence of vaccine hesitancy over several decades has resulted in its inclusion in the list of the top 10 global health threats by the World Health Organization (WHO) in 2019.[8] COVID-19 is a newly emerging infectious disease, and the uncertainty of newly developed vaccines may further exacerbate public concerns about vaccination.[9] This means that vaccine hesitancy also plays a crucial role in the vaccination campaign in response to the COVID-19 pandemic, identifying it as a significant public health threat. Therefore, getting people to overcome vaccine hesitancy and promote the vaccination process of various kinds of vaccines is one of the critical challenges global public health continues to face.

Existing research on vaccine hesitancy mainly focuses on the influencing factors and solutions of vaccine hesitancy. Regarding the factors that influence vaccine hesitancy, scholars specifically discussed factors such as population, vaccine accessibility, cost of vaccination, personal responsibility, risk perception, preventive measures, trust in health authorities and vaccines, safety and efficacy of vaccines, and other information about vaccines. Regarding solutions for vaccine hesitancy, scholars focused on how people's willingness to accept vaccination can be increased, the feasibility of compulsory vaccination, and how to improve the convenience of vaccination. During the COVID-19 pandemic, research on vaccine hesitancy has added considerable new data to previous research conclusions. First, because of the short research and development time of COVID-19 vaccines and the complex information dissemination channels, people were skeptical about the safety and effectiveness of the COVID-19 vaccine. Compared with other vaccines, this made vaccine hesitancy more likely. Second, regarding the solution to vaccine hesitancy, most scholars believe that to increase people's willingness to accept vaccination, accurate and detailed information should be provided to the public through reliable and convenient channels. Third, the vaccination of leaders, healthcare workers, and others can also set an example for the public and improve the COVID-19 vaccination coverage rate. In general, although the academic community has profoundly discussed the research on vaccine hesitancy by employing phenomenological analyses, the existing research has not arrived at a universal and general explanation of the causes of vaccine hesitancy. This research gap prevents decision-makers from forming a global consensus on how to alleviate vaccine hesitancy, thus slowing down the process of continuous improvement of the global public health status.

As a universal social dilemma, the collective action dilemma caused by free riding behavior has long puzzled researchers and practitioners across many fields. At present, the impacts of the collective action dilemma have been

CONTACT Shifei Zhang zhangshifei@st.gxu.edu.cn School of Public Policy and Management, Guangxi University, 100 East University Road, Nanning 530004, China.

observed in common resources management, food safety management, environmental management, urban management, and other fields involving public organizations, public safety, and public health.[10–14] Together, from the perspective of collective action, public problems provide the academic circle with a clear and unified idea for understanding, explaining, and solving relevant problems. Therefore, the theoretical logic of collective action has become a systematic, emerging, and fruitful perspective for diagnosing problems in the public sphere.

This paper addresses the following two main questions: (1) Can the free riding behavior problem provide a valid perspective to explain the causes of vaccine hesitancy? (2) How can the impact of the free riding behavior problem on vaccine hesitancy be mitigated? Many phenomena reflect the correlation between vaccine hesitancy and free riding behavior. This paper takes the vaccination with the novel COVID-19 vaccine as example. Based on a questionnaire survey from China, the correlation between the collective action dilemma and vaccine hesitancy is explored. Further, the possibility of adopting selective incentive and collective action measures in the process of solving the vaccination collective action dilemma is discussed. Finally, this paper discusses feasible solutions to mitigate the impact of free-riding behavior on vaccine hesitancy from the following two aspects: the use of incentives or penalties to get people vaccinated and the participation of multiple subjects in public health governance. This paper suggests that addressing vaccine hesitancy requires a multifaceted approach that involves education, incentives, and penalties. By working together, individuals, communities, and governments can help to ensure that everyone has access to safe and effective vaccines and can enjoy the benefits of herd immunity.

This paper contributes to the literature in the following two aspects: On the one hand, by studying COVID-19 vaccine hesitancy, this paper contributes a new variable to the factors affecting vaccine hesitancy; on the other hand, scholarly research on collective action theory primarily focuses on small-scale, regional, and closed public resource governance, without discussing large-scale, cross-border, and open commons. This paper discusses the relationship between collective action dilemmas and vaccine hesitancy. In fact, it is an exploration and attempt to push collective action theory into the broad field of human behavior.

Literature review

General influencing factors of vaccine hesitancy

Based on existing research, the factors influencing vaccine hesitancy can be subdivided into demographic factors influencing vaccination (e.g., race, age, gender, pregnancy, education, and employment). Other factors are the accessibility and cost of vaccination, personal responsibility, risk perception, precautionary measures taken based on the decision to vaccinate, trust in health authorities and vaccines, safety and efficacy of novel vaccines, and access to vaccine information.

Demography is discussed first: Race, age, sex, pregnancy, education, and employment are common demographic factors influencing vaccine hesitancy. Mesch and Schwirian (2015) argued that Caucasian and Hispanic populations living in the USA are more likely vaccinated than black populations.[15] Ferrante (2011), Myers and Goodwin (2011), Rönnerstrand (2013), and Mesch and Schwirian (2015) suggested that older people are more likely to be vaccinated than younger people.[15–18] Ferrante (2011) and Gilles (2011) suggested that men are more likely to be vaccinated than women and that men commonly believe that vaccination is more effective than women.[16,19] Hilton and Smith (2010), Steelfisher (2011), and Cassady (2012) found that pregnant women in the UK and the USA expressed concerns over how vaccination may affect their baby, which led them to vaccinate.[20–22] At the same time, Hilton and Smith (2010) found that pregnant women perceived that there were mixed messages regarding medication during pregnancy which could decrease vaccine uptake in the UK.[20] A Swedish study reported that lower education and income might reduce vaccination frequency.[23] Another US study found that the unemployed were more likely to seek vaccination.[24]

Accessibility and cost of vaccination: Accessibility and vaccine cost are essential factors people consider before deciding whether to accept vaccination.[22,25–28] Research showed that vaccine availability and the speed of vaccination influenced people's decision to vaccinate. In Canada, participants who could be vaccinated through a primary care clinician or a short-term clinic were more likely to be vaccinated.[29] In Nigeria, India, Pakistan and Greece, longer distances to the vaccination delivery point, either real or perceived, were a significant barrier.[30–33]

Personal responsibility and risk perception: On the one hand, vaccination is a social responsibility that transcends barriers such as long waiting times.[20,29] For example, vaccinated individuals reported an emphasis on protecting themselves, their communities, and high-risk family members to prevent disease transmission.[23,29,34] On the other hand, individual risk perception may hinder vaccination. For example, in Sweden and Switzerland, participants in subjective good health had a lower willingness to accept vaccination than participants in poor health.[19,23,35]

Precautionary measures, taken based on the decision to vaccinate: People who choose to get vaccinated are more likely to also take other precautions to control the spread of the disease. A Swedish study showed that the frequency of hand washing, reporting coughs and sneezes, and the use of disinfectants were all higher in vaccinated people than in unvaccinated people.[23]

Trust in health authorities and vaccines: People's trust in medical information from health service organizations and their social peers influenced their decision to be vaccinated. For example, in four studies on Canada, France, Sweden, and the USA, trust in health authorities was generally associated with higher willingness to vaccinate.[15,23,29,36] In addition to trust in health service organizations, people who trusted governments also had higher vaccination effectiveness.[19,21,37]

Safety and effectiveness of the vaccine. Participants reported greater fear and uncertainty about the safety, efficacy, and residual long-term side effects of vaccines, i.e., people's concerns about the safety and efficacy of vaccines may increase their degree of vaccine hesitancy.[17,22,29,34,38,39]

Access to vaccine information: Lack of vaccination information and access to misinformation influence people's decision to vaccinate.[17,20,29,36,40–42] A lack of adequate information about vaccination or an encounter with conflicting information from different sources may reduce an individual's willingness to vaccinate.[29,43] While the Internet was a valuable resource for disseminating crucial public health information during the COVID-19 pandemic, a lack of clear and consistent information may prevent people from getting vaccinated.[36]

In addition, vaccination is part of the "wider social world," which means that different factors (such as past health service experiences, family history, sense of control, and conversations with friends) influence the vaccination-related decision-making process.[44]

New features of vaccine hesitancy during the COVID-19 pandemic

Since the beginning of 2020, COVID-19 has spread rapidly across the globe. Its negative effects are more apparent than in previous diseases, and people have different attitudes on whether to accept vaccination.[45] The new features of vaccine hesitancy in the COVID-19 era are summarized in the following:

First, it took far less time to develop COVID-19 vaccines than other vaccines, leading to doubts about their safety and effectiveness. Hooper (2021) pointed out that concern over the speed of COVID-19 vaccine development was one of the important reasons affecting people's willingness to accept vaccination.[46] A study from the UK also reported doubts and concerns about vaccine effectiveness and potential side effects, especially in the context of rapid vaccine development and accelerated testing.[47]

Second, as a newly developed vaccine, the scientific nature and universality of information dissemination of the COVID-19 vaccine were limited by time. The resulting lack of information on new vaccines also made the public hesitant and skeptical about COVID-19 vaccines. Several studies have found greater fear and uncertainty about the safety, efficacy, and residual long-term side effects of new vaccines.[17,22,29,34] Many people who are actually willing to be vaccinated wanted to wait as long as possible to gain more vaccination experience from others.[48] A study from China showed that the general public believed that the safety and effectiveness of vaccines were not sufficiently convincing, which decreased their willingness to vaccinate against COVID-19.[49] A UK study showed that concerns about the side effects and safety of vaccination – especially negative effects in the future – were the main reason for vaccine hesitancy.[50] Concerns are that these vaccines have not been tested rigorously enough to identify all possible adverse events and efficacy in a scientific manner.[51] The fact that vaccine hesitation has decreased over time further proves that uncertainty generated by new vaccines is more likely to produce vaccine hesitancy.[51–53]

Third, COVID-19 vaccines were developed in an era of rapid information transmission. Regarding the information on COVID-19 vaccines presented by various media outlets, it is generally difficult for the general public to distinguish between true and false statements, which easy leads to a mislead public. Evidence indicates that people are less likely to accept a vaccine even as it becomes widely available if they believe misinformation about the virus, and beliefs about the origin of COVID-19 are particularly important in this context.[54,55] Lockyer and Islam (2021) argued that in the process of the COVID-19 pandemic, erroneous information about the pandemic caused public anxiety, which led to people's hesitation to vaccinate against COVID-19.[56] Hou and Tong (2021) found that vaccine hesitancy is widespread worldwide.[57] Negative tweets attract higher engagement on social media, which has gradually become the main platform against vaccination.[58]

Fourth, because of a lack of information on COVID-19 vaccines, people tend to use other factors that are related to vaccines and outbreaks as the basis for vaccination decisions. Examples are their trust in authorities or vaccine developing companies, judgment on the COVID-19 outbreak itself, judgment on one's own immunity and health, and past vaccination experiences. Prior research suggests that COVID-19 vaccine hesitancy is associated with a lack of trust in the government.[59–61] Susceptibility to COVID-19 and the perceived benefits of vaccination play a role in mitigating COVID-19 vaccine hesitancy.[51] In addition, the degree of the perceived risk of COVID-19 also affects vaccine hesitancy. In the Oxford Coronavirus Explanations, Attitudes, and Narratives Survey II (OCEANS-II), low awareness of virus risk was a key factor in vaccine hesitancy.[62] Allington (2021) suggested that vaccination hesitancy is related to a low-risk perception of COVID-19.[63]

Ways to reduce COVID-19 vaccine hesitancy

Certain scholars believe that providing accurate and detailed information to the public through reliable and convenient channels can ease COVID-19 vaccine hesitancy. On the one hand, providing the public with information about COVID-19 vaccines through reliable and convenient channels can reduce people's hesitation to vaccinate against COVID-19. Vaccine delivery systems and governments are important sources of vaccine-related information for the public and play a key role in alleviating vaccine hesitancy.[64] Vaccine hesitancy for COVID-19 vaccines can be addressed by systematically promoting more reliable sources of information, such as through peers, teachers, and official websites.[51] Information campaigns through platforms that are commonly used by vaccination hesitant people, such as spreading information between entertainment programs (such as TV dramas), can effectively increase the coverage of COVID-19 vaccination.[65] On the other hand, the provision of accurate and detailed information to the public can reduce people's hesitation to vaccinate against COVID-19. For example, accurate and timely dissemination of information on COVID-19 vaccines and comprehensive measures can increase the willingness to vaccinate and confidence in vaccination of the population before vaccination.[49] In addition, the vaccination of leaders, healthcare workers, and others can also set an example and improve the coverage rate of COVID-19 vaccination.[66]

Summary on the literature review

In conclusion, the factors affecting vaccine hesitancy and mitigation measures have been fully discussed in existing studies, but there are still directions worthy of further exploration. First, the discussion on the factors of vaccine hesitancy mostly remains at the phenomenological level, lacking common rules and a systematic summary. Second, solutions to mitigate vaccine hesitancy are limited to specific measures and have yet to form a global consensus solution. Third, schemes for mitigating COVID-19 vaccination hesitancy have not been systematically explored.

Theoretical analysis and hypotheses

Theoretical analysis

The effect of free riding behaviour on the number of vaccinated people in society

Collective good requires collective action. Wright et al. (1990) provided the following definition of collective action: "A person is engaged in collective action if he/she acts like a typical member of the group to which he/she belongs, and if his/her actions are intended to improve the situation of the group to which he/she belongs.[67]" According to this definition, collective action is a form of intergroup behavior, which is an action strategy with the aim to improve the status of the group. Therefore, collective action differs from interpersonal behavior with the aim to improve the status of individuals. Individuals who accept vaccination can not only acquire immunity themselves, but also further increase the safety of other members of society. In other words, the safety of each social member is achieved by vaccinating all members of society. In this respect, the sense of security of each social member is achieved by the collective action of all social members to get vaccinated together. Therefore, in the process of vaccination, the collective good provided by the members of society through the collective action of joint vaccination triggers a sense of security in the whole society. In this way, everyone in society can obtain their own individual safety from this sense of security.

Free riding behavior emerges easily in collective action. The free riding behavior in the vaccination process can be manifested as the behavior of individuals who deliberately do not want to bear the costs incurred in the vaccination process because they can increase their own safety via the vaccination of others. Whether vaccines, especially newly developed vaccines, carry potential risks for human health remains unknown. In this case, people have two choices with regard to vaccination: (1) People can choose to be vaccinated, which causes a certain time and monetary cost in the vaccination process, as well as the cost of bearing potential vaccination risks. (2) People can choose not to be vaccinated, and enjoy the benefits resulting from other people's vaccinations at zero cost. Faced with this choice, the economic man tends to choose the latter, i.e., free riding behavior. When the majority of people choose free riding behavior based on their own rational considerations, it becomes highly likely that, within a certain period of time, only a few people will choose to pay the cost of vaccination. In this case, social and public safety cannot be effectively guaranteed, and vaccination has fallen into the dilemma of collective action, which is reflected as the vaccine hesitancy that can be observed today.

This section explains the collective action dilemma people face in their vaccination decisions. Based on Olson's (1965) analysis of the logic of collective action, Figure 1 illustrates how collective action dilemmas arise during the vaccination process.[10] The horizontal axis represents the number of inoculated people in the whole society, the vertical axis represents the increase in the sense of security individuals gain from the improvement of social safety (i.e., the marginal revenue of individuals), and the marginal cost of vaccination for individuals corresponds to the increase in the number of vaccinated people in society. In Figure 1, curve C represents the individual marginal cost of providing the collective good. Because the time and effort required for individuals to get vaccinated are related to the distance between the individual and the vaccination site, while the risk of the vaccination is only

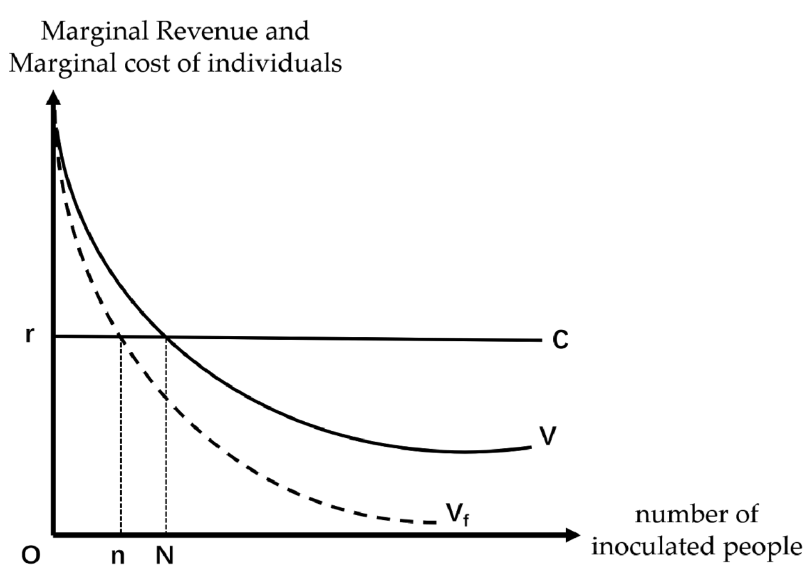

Figure 1. The collective action dilemma in the vaccination process.

related to the novelty of technology, the cost of individual vaccination remains relatively fixed, regardless of the number of people vaccinated in society. Thus, curve C in Figure 1 is a horizontal line that is parallel to the horizontal axis. In Figure 1, curve V represents the marginal revenue individuals gain from collective good. As the number of vaccinated people in society increases, the overall safety in society increases, while the marginal increase in the sense of security individuals can derive from the act of vaccination decreases. Thus, curve V in Figure 1 is a curve that decreases toward the lower right.

According to Olson (1965),[10] the necessary condition for people to get vaccinated is that the individual benefit from the collective good (V) is greater than the cost of the individual participating in the provision of the collective good (C). This condition corresponds to the range from O to N in Figure 1 of the number of people vaccinated. When the number of vaccinated people in the whole of society reaches N, the benefits obtained by individuals from vaccination and the associated costs will be balanced: the equilibrium marginal revenue of the individual is r and the equilibrium marginal cost of the individual is C. In this case, the collective good social security provides via the act of vaccination achieves an optimal level.

Considering the effect of free riding behavior on vaccination, free riding behavior occurs when people realize that they can benefit directly from the vaccination of others and that there is no cost involved in the process. In this case, if someone does not get vaccinated, the security of other individuals is actually reduced. This actually reduces the benefit that the individual receives from the collective good, and ultimately leads to the individual's marginal revenue curve falling from V to Vf. At this time, the number of vaccinated people n finally achieved by society is lower than the number of vaccinated people N required for the optimal supply of the collective good; consequently, the whole of society cannot achieve an effective supply of social safety at this time. At this point, the vaccination will fall into a collective action dilemma, and the vaccine hesitancy problem will become widespread in society.

Research hypotheses

Based on the previous analysis of Figure 1, this paper proposes the following theoretical hypotheses:

H1: Free riding behavior during vaccination can lead to vaccine hesitancy.

In the following sections of this paper, these hypotheses are tested through empirical analysis.

Data sources, variable selection, and methods

Data sources

The data used for this study originate from the project "Exploring COVID-19 Vaccination Hesitation from the Perspective of Free Riding Behavior" conducted by the School of Public Administration of Guangxi University in December 2022. This survey refers to the methods of Wang, Chao, Han (2021) as well as Wang and Lu (2021).[49,68] When the whole society faced travel restrictions because of the COVID-19 pandemic, online questionnaires were issued to collect data. From December 7, 2022, to February 7, 2023, the project team used stratified random sampling to conduct an anonymous online cross-sectional survey on Wen Juanxing (China Limited), the largest online survey platform in China. Questionerstar – the Chinese equivalent of Qualtrics, SurveyMonkey, or CloudResearch – provides online questionnaire design and survey capabilities for businesses, research institutions, and individuals. The Sample Database of Wen Juanxing platform covers the responses of more than 2.6 million respondents whose personal information was confirmed to provide a true, diverse, and representative sample. The target population of this study is Chinese adults living in mainland China. Therefore, a random sampling procedure stratified by age and location was used to match Chinese adults in the Wen Juanxing sample database. The respondents matched in this study were recruited from December 7, 2022, to February 7, 2023. These respondents joined voluntarily and were paid through the Wen Juanxing platform. The entire process of recruiting respondents followed international research guidelines. The survey covers basic information of the respondents, their vaccination situation, their hesitation to vaccinate against COVID-19, and the measures taken by the country and community to alleviate their hesitation to vaccinate against COVID-19.

It should be noted that this method of surveying respondents online is prone to the problem of common method bias, which is a common problem of self-report questionnaires. The main reasons for this problem are motivation consistency, implicit correlation bias, default tendency, mood state, and transient emotion. To overcome the problem of common method bias, this study adopted the following two approaches when conducting the survey and in the data analysis process: First, at the start of the questionnaire, respondents were assured that the survey was anonymous and that their personal private information would be strictly protected. This meant that respondents could fill in the survey with complete confidence and less speculation about the purpose of the study. Second, this study referred to Gao et al. (2016), Gao et al. (2015), and Jones et al. (2015) to identify how to improve the reliability of respondents' feedback in unsupervised subjective questionnaires.[69–71] This paper introduced several "trap questions" that were logically related to each other. The responses to these "trap questions" were used to determine whether the respondents had adverse reactions, intentionally provided useless information, and/or provided false information. Samples that failed the trap question were eventually eliminated to minimize the impact of common methodology bias on the study, thus further improving data credibility.

A total of 2,259 questionnaires were collected in this survey. After collecting the questionnaires through the network platform, the research team excluded unqualifying samples from the overall sample according to the following principles: (1) the answers to subjective questions do not conform to normal logic; (2) apparent logical errors appear before and after the answer; (3) the question selection shows clear regularity (such as continuous oblique filling); (4) the time taken to complete the questionnaire was excessive; (5) incorrect answers were given to trap questions. Finally, 2203 valid questionnaires remained after screening, and the overall effective response rate was 97.52%.

The questionnaire survey has been approved by the respondents. Specifically, before officially answering the questions, respondents were prompted to read a pre-designed Online Participant Consent Form on the first page (see Appendix A). After understanding the contents of the survey, respondents were free to choose whether to start answering questions online. Meanwhile, to further ensure the freedom of the respondents, the research team also added a function that allows the respondents to freely exit the answer page in the questionnaire at any time. This allowed the respondents to freely terminate the answering process of the online questions. The questionnaire survey was conducted anonymously.

Variable selection

Dependent variable

In this study, the dependent variable was vaccination hesitancy (VH). Existing studies mainly measure vaccination hesitancy of the COVID-19 vaccine through two methods. One method is the direct inquiry method, where people are directly asked about their willingness to get vaccinated against COVID-19 as a measure of people's vaccinate COVID-19 hesitancy;[63,66] another example is to ask people directly how hesitant they are to get vaccinated against COVID-19.[61] The other method is the time to vaccination measure, which measures people's hesitation to vaccinate using the time between COVID-19 vaccines have become available and the actual vaccination (immediate vaccination, waiting a while, waiting a long time, not vaccinating) [62,71]. In this paper, based on the research of Freeman et al. (2021) and Soares et al. (2021), the situation of data acquisition, and research practice, the method of measuring the time until vaccination was used.[62,72] The question "Attitude when I first knew I could get the vaccine" (1 = I got the vaccine immediately, 2 = I waited for the vaccination, 3 = I waited for the vaccination for a long time, 4 = I have not received the vaccine yet) was selected as the dependent variable to measure vaccination hesitation.

Core independent variable

The core independent variable of this paper is the free riding behavior phenomenon (FR) in the process of COVID-19 vaccination. In the case of COVID-19 vaccination, free riding behavior manifests itself as the act of waiting for someone else to be vaccinated first to provide social security, thereby enabling increased personal safety at no cost. Therefore, in this paper, the question of "Whether in the process of COVID-19 vaccination, there has been a wait-and-see behavior and waiting for others to be vaccinated" (yes = 1, no = 0) is used to measure whether the respondent ever showed free riding behavior in the process of vaccinating against COVID-19.

Control variables

First, demographic factors are controlled. For the selection of control variables in terms of population factors, this paper mainly refers to the studies of Wang and Xinran (2021) as well as Wang and Han (2021).[49,68] Wang and Xinran (2021) considered changes in the acceptance of COVID-19 vaccination at different stages of the pandemic in China, and examined factors such as age, sex, education level, marriage, location (east, west, or central), location (urban/rural), employment, health status, income level, and other demographic characteristics on vaccine hesitancy.[68] In contrast, Wang and Han (2021) considered the influence of different provinces and occupations on vaccine hesitancy.[49] In particular, in terms of occupation, Wang and Han (2021) proposed that medical personnel, government or social security personnel, public service personnel, traffic and port personnel, or customs personnel should be considered a priority for vaccination.[49] In summary, the demographic characteristics of age (AGE), sex (GENDER), education level (EDU), marriage (MAEEIGE), province, main living area (DISTRICT) in the last two years, employment and occupation, health status (HEALTH), and monthly income (INCOME) are mainly assessed in this paper. In particular, when considering employment and occupation, special occupations such as medical staff, students, customs and port staff, civil servants, and public institution staff are treated separately in this paper.

Second, as a new vaccine with a short research and development time, the safety and effectiveness of the COVID-19 vaccine can easily be questioned, which affects people's willingness to get vaccinated with a COVID-19 vaccine. According to the research of Myers and Goodwin (2011), Cassady et al. (2012), Boerner et al. (2013), Determann et al. (2015), and Freeman et al. (2020),[17,22,29,34,47] when designing control variables, the question "Do you worry about the safety of the COVID-19 vaccine?" (1 = strongly disagree to 5 = strongly agree) was selected to measure people's concerns about the safety of COVID-19 vaccines (SECURITY). The question "Do you think the effect of the COVID-19 vaccine is limited?" (1 = strongly disagree to 5 = strongly agree) was used to measure people's concerns about the effect of the COVID-19 vaccine (EFFECT).

Third, the COVID-19 vaccine was developed in an era of rapid information transmission. It is difficult to distinguish between true and false information on both the COVID-19 vaccine and the pandemic coming from various media outlets, making it easy to mislead the public. Information about available COVID-19 vaccines, information about COVID-19 outbreaks, and the source of information influence people's willingness to get vaccinated. Therefore, according to the research of Lockyer and Islam (2021), Verger and Dube (2020), and Jain (2021),[51,56,58] when designing control variables, the question "Is the information you usually receive about COVID-19 vaccine positive or negative?" (1 = extremely negative to 5 = very positive) was selected to measure the information (CVI) people receive about the COVID-19 vaccine. The question "Is the information you receive about COVID-19 positive or negative?" (1 = extremely negative to 5 = very positive) was selected to measure the information people received about COVID-19.

Fourth, because of the lack of information on COVID-19 vaccines, people tend to use other factors related to vaccines and outbreaks as the basis for their vaccination decisions.

Individual risk perception may hinder vaccination,[19,23] while trusting the services of the WHO and governments resulted in a higher vaccination effectiveness.[19,24,37] Based on this, the question "Your attitude toward the current COVID-19 pandemic" (1 = very worried to 5 = full of confidence) was selected to measure personal risk perception (PRP) when designing control variables. The question "How would you rate the service capacity of the vaccination facility in your area" (1 = very poor to 5 = very good) was selected to measure people's trust in the local health service level (SC). The question "Do you agree or disagree with the statement that people should do things according to the instructions of the state" (1 = strongly disagree to 5 = strongly agree) was used to measure trust in government (GT). Table 1 presents descriptions and statistical analyses of the variables selected in this paper.

Methods

Ordered probit regression

The dependent variable selected in this study is a discrete variable of the natural order the distribution of which does not meet the requirements of the ordinary least squares model. Therefore, the dependent variable must be analyzed with in a ranking model, such as ordered probability regression.

Assuming $y^*= x'\beta + \varepsilon$ (y^* is an unobservable variable), the se-lection rule is given by:

$$y = \begin{cases} 1\, if & y^* \le u_1 \\ 2\, if & u_1 < y^* \le u_2 \\ 3\, if & u_2 < y^* \le u_3 \\ 4\, if & u_3 < y^* \le u_4 \\ 5\, if & u_4 < y^* \end{cases} \tag{1}$$

where the parameter $u_1 < u_2 < u_3 < u_4$ to be estimated is the "cutoff point." Assuming $\varepsilon \sim N(0,1)$ (normalize the variance of the perturbation term ε to 1), we have:

$$\begin{aligned} P(y=0|x) &= P(y^* \le r_0|x) = P(\mathbf{x}'\boldsymbol{\beta} + \varepsilon \le r_0|x) \\ &= P(\varepsilon \le r_0 \ - \mathbf{x}'\boldsymbol{\beta}|x) - \Phi(r_0 - \mathbf{x}'\boldsymbol{\beta}) \\ P(y=1|x) &= P(r_0 \le y^* \le r_1|x) = P(y^* \le r_1|x)\ P(y^* \le r_0|x) \\ &= P(\mathbf{x}'\boldsymbol{\beta} + \varepsilon \le r_1|x) - \Phi(r_0 - \mathbf{x}'\boldsymbol{\beta}) \\ &= P(\varepsilon \le r_1 \ - \mathbf{x}'\boldsymbol{\beta}|x) - \Phi(r_0 - \mathbf{x}'\boldsymbol{\beta}) \\ &= \Phi(r_1 - \mathbf{x}'\boldsymbol{\beta}) - \Phi(r_0 - \mathbf{x}'\boldsymbol{\beta}) \\ P(y=2|x) &= \Phi(r_2 - \mathbf{x}'\boldsymbol{\beta}) - \Phi(r_1 - \mathbf{x}'\boldsymbol{\beta}) \\ &\cdots\ \cdots \\ P(y=J|x) &= 1 - \Phi(r_{J-1} - \mathbf{x}'\boldsymbol{\beta}) \end{aligned} \tag{2}$$

In this way, the sample likelihood function is obtained to further obtain the Maximum Likelihood Estimation estimator, namely the ordered probability model.

Endogeneity problem and propensity score matching

Simple ordered probit regression does not consider the endogenous problem caused by sample selectivity bias. That is, in ordered probit regression, people with a high tendency to show free riding behavior and people with a low tendency to show free riding behavior are different individuals. Because there are many differences between different individuals, they may have different participation degrees even if they are not affected by free riding behavior or if both have the same tendency to show free riding behavior. Therefore, the existence of free riding behavior in the ordered probit model is not necessarily the reason for people's vaccine hesitancy against COVID-19.

Table 1. Variables and their descriptive statistics.

Variable	Description	Mean	Std. Dev.	Min	Max
Dependent variable	N = 2203				
Dependent variable					
VH	Attitude when I first knew I could get the vaccine (1 = I got the vaccine in the first place; 2 = I waited for the vaccine; 3= I waited for the vaccine for a long time; 4 = I have not received the vaccine yet)	1.532	0.651	1	4
Core independent variable					
FR	Whether in the process of COVID-19 vaccination, there has been a wait-and-see behavior and waiting for others to be vaccinated (yes = 1, no = 0)	0.616	0.487	0	1
Control variables					
AGE	Age	31.409	7.736	10	62
GENDER	Male/female	1.541	0. 498	1	2
EDU	Below primary school/primary school/middle school/high school/bachelor's degree/master's degree/doctoral degree	4.986	0.496	1	7
MAEEIGE	Married/otherwise	1.259	0.438	1	2
DISTEICT	Urban/rural areas	1.080	0.271	1	2
HEALTH	How healthy do you think you are? (1 = very unhealthy to 5 = very healthy)	3.578	0.816	1	5
INCOME (LN)	______ CNY/month	8.646	1.531	0	12.429
SECURITY	Do you worry about the safety of the COVID-19 vaccine (1 = strongly disagree to 5 = strongly agree)	2.825	1.148	1	5
EFFECT	Do you think the effect of the COVID-19 vaccine is limited (1 = strongly disagree to 5 = strongly agree)	3.049	1.165	1	5
CVI	Is the information you usually receive about the COVID-19 vaccine positive or negative? (1 = extremely negative to 5 = very positive)	3.843	0.764	1	5
CSI	Is the information you receive about COVID-19 positive or negative? (1 = extremely negative and 5 = very positive)	3.698	0.859	1	5
PRP	Your attitude toward the current COVID-19 epidemic (1= very worried –5= full of confidence)	3.797	1.036	1	5
SC	How would you rate the service capacity of the vaccination facility in your area (1= very poor –5= very good)	4.040	0.699	1	5
GT	Do you agree or disagree with the statement that people should do things according to the instructions of the state (1= strongly disagree –5= strongly agree)	4.081	0.800	1	5

To control the endogeneity problems caused by sample selection bias and identify the real causes of participation difficulties, this paper conducts propensity score matching (PSM). This also helped to overcome the influence of sample selection bias and identify the real cause of vaccine hesitation. The concept of the propensity score was proposed by.[73] They defined propensity score as the conditional probability that an individual is affected by certain independent variables after controlling for observable "confounding" variables. The use of the control propensity score to obtain causality between phenomena can exclude the influence of "confounding" variables and thus disclose a "net effect" between the two phenomena. This approach ensures that the conclusion is reliable. The statistical principles of PSM are detailed in Appendix B.

Results

Free riding behaviour affects vaccine hesitancy

Table 2 shows the results obtained using ordered probability regression in Stata 17.0. Model 1 is the single regression of free riding behavior. The results show that free riding behavior had a significant positive effect on vaccine hesitancy, indicating that free riding behavior leads people to hesitate and wait for a longer time before getting vaccinated against COVID-19. Models 2–6 are the result of the gradual addition of each group of control variables. The estimation results show that free riding behavior had a significant positive effect on vaccine hesitancy in the process of gradually adding control variables. This result indicates that free riding behavior causes people to hesitate and wait for longer before they get vaccinated against COVID-19.

Test results of propensity score matching

To address the endogeneity problem associated with sample selection bias, the nearest neighbor matching method, the radius matching method, and the kernel matching method of PSM were applied. The average treatment effect for the treatment (ATT) of free riding behavior on vaccine hesitancy was estimated. The standard deviations of all matched variables were calculated in reference to Lechner (1999), Sianesi (2004), and Caliendo et al. (2008).[74–76] T-tests were conducted for individual variables and the whole sample. The overall sample balance test of each matching method is shown in Table 3. In all matching methods, the absolute values of the standard deviations of all matched variables remain within 10%, and the difference after matching was non-significant. This result implies that all matching variables had good balance after matching, thus indicating that the PSM result is reliable.

The common support hypothesis necessitates that the propensity scores of both the treatment group and the control group have a large common support domain, thus ensuring

Table 2. Regression results.

	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
FR	1.169***	1.176***	0.885***	0.854***	0.840***	0.831***
	(0.059)	(0.060)	(0.065)	(0.065)	(0.065)	(0.066)
AGE		0.006	0.005	0.005	0.004	0.008*
		(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
GENDER		−0.091*	−0.105*	−0.101*	−0.102*	−0.098*
		(0.053)	(0.054)	(0.054)	(0.054)	(0.055)
EDU		−0.047	−0.052	−0.052	−0.052	−0.054
		(0.055)	(0.056)	(0.056)	(0.056)	(0.057)
MAEEIGE		0.088	0.121*	0.068	0.059	0.054
		(0.071)	(0.072)	(0.073)	(0.073)	(0.074)
DISTEICT		−0.146	−0.159	−0.157	−0.157	−0.132
		(0.101)	(0.103)	(0.103)	(0.104)	(0.105)
HEALTH		−0.102***	−0.079**	−0.043	−0.031	−0.025
		(0.032)	(0.033)	(0.034)	(0.034)	(0.035)
LANCOME		−0.044**	−0.041**	−0.037*	−0.039**	−0.048**
		(0.019)	(0.019)	(0.019)	(0.020)	(0.020)
SECURITY			0.334***	0.297***	0.292***	0.307***
			(0.029)	(0.029)	(0.030)	(0.030)
EFFECT			0.035	0.023	0.017	0.006
			(0.027)	(0.028)	(0.028)	(0.028)
SC				−0.122***	−0.088*	−0.086*
				(0.043)	(0.045)	(0.046)
CPI				−0.108***	−0.093**	−0.094**
				(0.041)	(0.041)	(0.041)
CVI				−0.046	−0.023	−0.024
				(0.046)	(0.047)	(0.047)
PRP					−0.055*	−0.048
					(0.029)	(0.029)
GT					−0.072*	−0.070*
					(0.037)	(0.038)
Province						Controlled
Observations	2203	2203	2203	2203	2203	2203
R^2	0.107	0.113	0.160	0.168	0.170	0.177
Chi^2	426.6	452.6	637.6	672.1	680.4	705.3
p	0.000	0.000	0.000	0.000	0.000	0.000

Standard errors are shown in parentheses; ***$p < .01$, **$p < .05$, *$p < .1$.

Table 3. Overall sample balance test of each matching method.

Matching method	Sample situation	Ps R2	LR Chi^2	P > Chi^2	Mean bias
Neighbor matching	Unmatched	0.192	564.05	0.000	23.4
	Matched	0.006	21.17	0.571	2.7
Radius matching	Unmatched	0.192	564.05	0.000	23.4
	Matched	0.006	22.42	0.495	3.2
Kernel matching	Unmatched	0.192	564.05	0.000	23.4
	Matched	0.006	21.01	0.580	3.0

that the integrated characteristics of both groups are similar. In this paper, a bar graph of the common support domain of the propensity score is used. This is then followed by an analysis of the degree of overlap between the propensity score interval of the treatment group and that of the control group, as well as the size of the sample loss during the matching process. Figure 2 intuitively shows that under those matching methods, the propensity scores of both treatment groups and control groups overlap widely in the interval. The overlap testing results indicate that these matching methods result in satisfactory overlap areas of both the control groups and the treatment groups, and all pass the common support test.

The results of the treatment effect of free riding behavior on vaccine hesitancy are shown in Table 4. Under the three matching methods, free riding behavior plays a significantly positive role in the formation of vaccine hesitancy. Thus, after the interference of endogenous problems has been overcome, free riding behavior is indeed the cause of vaccine hesitancy. Hypothesis H1 is thus proved.

A feasible solution to the impact of free-riding behavior on vaccine hesitancy

The collective action dilemma associated with vaccine hesitancy emerges when individuals choose not to get vaccinated against a disease – despite their best interest to do so – because they believe that the benefits of vaccination can be shared by others who have not been vaccinated. This can create a situation where too few people are vaccinated to provide herd immunity, thus increasing the risk of outbreaks and

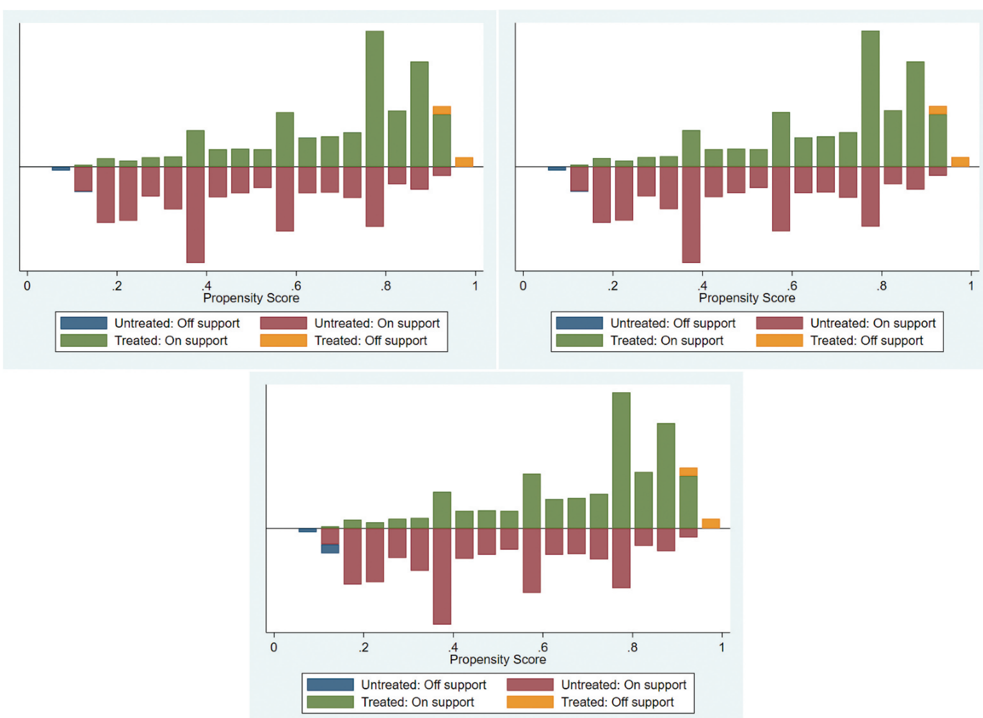

Figure 2. Overlap in testing results.

Table 4. Results of the treatment effect of free riding behavior.

Matching Method	Treated	Controls	ATT diff	T-stat	Sig
1:4 nearest neighbor matching	1.731	1.373	0.359	9.45	***
Radius matching	1.732	1.373	0.359	9.94	***
Kernel matching	1.732	1.379	0.353	10.27	***

1 ** represents significance at the level of 5%. 2 (Samples'), (the chosen caliper range) caliper = 0.06, which represents one-to-one matching and radius matching among observed values with a difference of the tendency score of 6%.

harming the community. Therefore, further discussion on alleviating the impact of free-riding behavior on vaccine hesitancy is worthy of discussion.

One possible solution to this dilemma is the use of incentives or penalties to encourage people to vaccinate. According to Olson (1973), an effective way to solve the free-riding behavior problem is to provide selective incentives to actors. A selective incentive implies the differentiated treatment of each member of a collective, including positive rewards and negative punishments, with the aim to create an "asymmetry" in the benefits of collective members. However, based on scientific, legal, and ethical concerns as well as practical effectiveness, mainly the positive rewards of selective incentives in solving the free riding behavior problem of vaccination are considered.[77] Positive rewards give those individuals who contribute to the collective good additional benefits in addition to the normal share of the collective benefit they have already gained. Additional benefits include both economic gains and social incentives that privilege those who contribute to the collective good.[77] In fact, in Olson's original formulation, selective incentives can better curb the free-riding behavior problem in small-scale collective action, but with expanding size of the collective, the cost and benefit issues will make collective action more and more unsustainable. However, in real life, it is not uncommon for large collectives to achieve common goals through collective action. The effectiveness of collective action involving a large number of members of society, such as the use of selective incentives to promote whole-society vaccination, has been tested and supported by practical research. Therefore, how selective incentives can be provided to actors with a tendency to show free-riding behavior associated with vaccination is a direction worthy of further research.

Vaccination passports, for example, portray a way to provide selective incentives to curb free-riding behavior in the vaccinating process. Specifically, if a citizen has been vaccinated with a COVID-19 vaccine, or if the citizen has suffered from COVID-19 or has recently tested negative using a nucleic acid test, the government will issue him/her a vaccination passport to prove that the holder is not, and cannot become, a source of infection for others.[78] By obtaining the passport, the citizen receives "privileges" in the form of being allowed to access public and private venues, benefitting from reduced access restrictions, and being able to move more easily. This line of argument suggests that people can be incentivized to get vaccinated by providing rewards that satisfy their with for convenience in their life. The findings of Oliu-Barton et al. (2022) also showed that coronavirus certificates have had a positive impact on vaccination rates in France, Germany, and Italy.[79] Therefore, it can be concluded that the use of selective incentives in accordance with local conditions can reduce the exacerbation of vaccine hesitancy caused by free-riding behavior.

In addition to adopting systematic governance methods such as vaccination passports, directly providing food and other goods is also an easy way to provide selective incentives. For example, Jarrett et al. (2015) argued that adopting an incentive-based (non-financial), i.e., encouraging vaccination by offering food or other goods to vaccinated people, is also a good way to increase vaccination rates in society.[80] This also reflects the role of selective incentives in promoting vaccination.

Another approach is to increase public awareness and education about the importance of vaccines and the risks of vaccine-preventable diseases. Educational campaigns may promote the benefits of vaccination, incentives (such as financial rewards or free vaccinations), and penalties (such as fines or restrictions on activities) for those who choose not to get vaccinated.[81,82] However, the effectiveness of these strategies can vary depending on the specific context and the targeted population. Under this situation, governments and health organizations can collaborate and provide accurate information about the safety and effectiveness of vaccines, and address any concerns or misconceptions people may have. Cairns et al. (2012) studied the effectiveness of promotional communication in the European region. They concluded that a series of campaigns jointly carried out by the state, health, and education departments can positively change the knowledge, attitude, and behavior of the population toward vaccination.[83] Chen et al. (2023) studied the change of COVID-19 vaccine hesitancy among residents in Guangzhou, China, over different periods; the results showed that the implementation of appropriate interventions led by the health sector as well as targeted programs implemented by the education sector was effective in addressing the possible risk of vaccine hesitancy.[84] Overall, addressing vaccine hesitancy requires a comprehensive approach that involves an understanding of its underlying reasons and developing targeted interventions to address these. By working together, governments, healthcare providers, and communities can help to ensure that everyone has access to safe and effective vaccines and that everyone can benefit from the protection provided by herd immunity.

At the same time, existing literature has shown that people with vaccine hesitancy are only temporarily "hesitant" and may need to take more time to decide, but such people will only delay vaccination instead of refusing to be vaccinated altogether. As long as people are finally able to choose to be vaccinated, the slight delay in vaccination caused by vaccine hesitancy will not impact the overall safety of society much.[85] The views of these studies seem to challenge the conclusions of the present paper. However, this paper argues that the relevant research views are reasonable, but based on such research, people cannot ignore other possibilities that exist objectively. That is, because free-riding behavior has been confirmed to be part of the vaccination process, if relevant measures are not taken to suppress it, the vaccination delay caused by vaccine hesitant people will probably evolve into refusal to get vaccinated in the end; therefore, widespread vaccine hesitancy will become a negative factor affecting public health. From this perspective, the conclusions of this paper do not contradict existing research, because this paper actually expands the discussion of more possibilities affecting vaccine hesitancy based on existing conclusions.

Discussion

This paper discusses the problem of free-riding behavior and how it influences vaccine hesitancy; new factors influencing vaccine hesitancy have been uncovered. Many existing studies on the factors affecting vaccine hesitancy have explored demographic factors, economic factors, personal moral factors, the attributes of the vaccine itself, and factors of the relationship between individuals and governments. Among them, demographic factors, personal moral factors, personal risk perception, personal experience, and family history can be summarized as individual independent factors. The economic factors and the attributes of the vaccine itself belong to external environmental factors. Factors such as an individual's trust in government authorities and access to vaccine information can be attributed to the connection between the individual and the environment. The existing research on the factors affecting vaccine hesitancy has focused on the internal characteristics of individuals and the relationship between individuals and the environment. In contrast, there has been little discussion on how relationships between humans affect vaccine hesitancy. Therefore, starting from the phenomenon of free-riding behavior between people, this paper discusses the impact of non-cooperation between people on vaccine hesitancy from the perspective of interpersonal relationships. This discussion can contribute new factors to the existing research on vaccine hesitancy from the perspective of cooperation between people.

Ostrom (1990) and Ostrom et al. (2007) pointed out that the discussion of all collective action dilemmas, including the free-riding problem, needs to be tailored to local conditions.[86,87] Therefore, this paper discusses the impact of free-riding behavior on vaccine hesitancy, which provides an analytical logic for current vaccine hesitancy research to cope with changes in reality and environmental shocks. As the public health research community responds to the new changes introduced by the COVID-19 pandemic, there is a real need for an analytical framework that reflects changes in the complex external environment. In this regard, the existing theories on solving the collective action dilemma caused by free riders have developed a relatively mature and viable framework for the robustness analysis of the social ecosystem. Therefore, if the effect of free-riding behavior on vaccine hesitancy can be confirmed in this paper, this robust analytical framework for studying how to overcome the collective action dilemma can be further introduced into the future analysis of vaccine hesitancy and other public health problems. Consequently, new theoretical and logical support can be provided for discussing public health issues under the changes and impacts of complex situations.

Instead of only relying on providing low-cost, reliable, and accurate information to solve the vaccine hesitancy problem, how to deal with broader public health problems, including vaccines through multi-subject cooperation, has gradually become the focus of scholars. In this paper, the phenomenon of free-riding behavior and its effect on vaccine hesitancy suggests that a multi-co-governance solution can be adopted to both solve the free-riding problem and provide an effective way to also solve the vaccine hesitancy problem. Therefore, this study provides a new entry point for research on vaccine hesitancy from the perspective of a pluralistic co-governance system. This will help to enrich future discussions and research to further address vaccine hesitancy.

Conclusion, implications, and limitations

Guided by the theory of collective action, in this paper, the relationship between free-riding behavior and vaccine hesitancy is analyzed using data from 2259 surveys from China and taking COVID-19 vaccine hesitancy as research object. The main conclusion of this paper is that free-riding behavior is an essential cause of vaccine hesitancy. This collective action dilemma in the vaccination process ultimately leads to vaccine hesitancy because of the existence of free-riding behavior where people attempt to enjoy the benefits of increased safety without paying the costs associated with vaccination. Based on this conclusion, this paper further discusses the effectiveness of the current selective incentive approach adopted by many countries in the process of solving the dilemma of collective action on vaccination, and presents feasible approaches to further alleviate the problem of vaccine hesitancy.

The research conclusions of this paper have two theoretical implications. First, previous studies have extensively explored various factors that influence vaccine hesitancy. However, the discussion on the factors leading to vaccine hesitancy mostly remained at the phenomenon level, lacking common rules and a systematic summary. This paper explains the causes of vaccine hesitancy from the perspective of free-riding behavior and provides a new perspective for a better understanding of vaccine hesitancy. Second, scholarly research on collective action theory mostly focuses on small-scope, regional, and closed public resource governance, while lacking discussions on large-scale, transboundary, and open public topics. This paper uses the COVID-19 vaccine that holds the potential to benefit the people as an example to discuss how people solve the problem of free-riding behavior in the process of enjoying the public benefits brought by the COVID-19 vaccine. Thus, the theory of collective action is applied to the study of human behavior in a broader field.

This study has some shortcomings. Vaccine hesitancy is a growing problem in many parts of the world and poses a substantial threat to public health. Despite the overwhelming evidence that vaccines are safe and effective, some individuals choose not to get vaccinated because of concerns about side effects, mistrust of the medical establishment, or misinformation spread through social media. This collective action dilemma on vaccine hesitancy can have serious consequences. When too few people get vaccinated against a disease, herd immunity breaks down, which means that even those who have been vaccinated may be at risk of contracting the disease. This can lead to outbreaks of vaccine-preventable diseases, such as measles, mumps, and rubella, which can cause severe illness and even death. Therefore, the question of how to deal with the impact of free-riding behavior on vaccine hesitancy has become a problem subsequent research must face. In this regard, because of the limitations imposed by practical conditions, this paper has not systematically discussed how to alleviate this problem after systematically proving that free riding impacts vaccine hesitation. This omission provides a clear direction for the research team's further research. In addition, there are actually many particularities in the COVID-19 vaccination process, such as whether it truly conveys immunity to the COVID-19 virus. These issues still need to be further explored. The existence of these particularities will challenge the presented research conclusions under special circumstances. Therefore, in the future, the impact of free-riding behavior on vaccine hesitancy in other vaccination processes needs to be further explored to expand the applicability of the conclusions of this paper.

Author contributions

Yiqing Su: contributed to the conception of the study, and significantly to analysis and manuscript preparation.

Xiaoting Zhang: conducted text analysis and manuscript writing of materials from field research.

Shifei Zhang: conducted text analysis and manuscript writing of materials from field research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the National Social Science Foundation (Grant No. 22GBL225).

ORCID

Shifei Zhang http://orcid.org/0000-0002-1224-7110

Data availability statement

The data that support the findings of this study are available from the corresponding author, [Shifei Zhang], upon reasonable request.

References

1. Kennedy J. Populist politics and vaccine hesitancy in Western Europe: an analysis of national-level data. Eur J Public Health. 2019;29(3):512–6. doi:10.1093/eurpub/ckz004.
2. Bunker JP, Frazier HS, Mosteller F. Improving health: measuring effects of medical care. Milbank Q. 1994;72(2):225–58. doi:10.2307/3350295.
3. Omer SB, Salmon DA, Orenstein WA, Dehart MP, Halsey N. Vaccine refusal, mandatory immunization, and the risks of vaccine-preventable diseases. N Engl J Med. 2009;360(19):1981–8. doi:10.1056/NEJMsa0806477.
4. Oostvogel PM, van Wijngaarden JK, van der Avoort HGAM, Mulders MN, Conyn-van Spaendonck MAE, Rümke HC, van Steenis G, van Wijngaarden JK. Poliomyelitis outbreak in an unvaccinated community in the Netherlands, 1992–93. Lancet. 1994;344(8923):665–70. doi:10.1016/S0140-6736(94)92091-5.
5. Center for Disease Control and Prevention (CDC). Notes from the field: pertussis—California, January–June 2010. MMWR Morb Mortal Wkly Rep. 2010;59:817.
6. Falagas ME, Zarkadoulia E. Factors associated with suboptimal compliance to vaccinations in children in developed countries: a systematic review. Curr Med Res Opin. 2008;24:1719–41. doi:10.1185/03007990802085692.
7. Xiao J, Cheung JK, Wu P, Ni MY, Cowling BJ, Liao Q. Temporal changes in factors associated with COVID-19 vaccine hesitancy and uptake among adults in Hong Kong: serial cross-sectional surveys. Lancet Regional Health-WesternlPacific. 2022;23:100441. doi:10.1016/j.lanwpc.2022.100441.
8. World Health Organization. Ten Threats to global health in 2019. Google Scholar; 2019 [accessed 2021 Mar 24]. https://www.who.int/emergencies/ten-threats-to-global-health-in-2019.
9. Kreps S, Prasad S, Brownstein JS, Hswen Y, Garibaldi BT, Zhang B, Kriner DL. Factors associated with US adults' likelihood of accepting COVID-19 vaccination. JAMA Netw Open. 2020;3(10):e2025594. doi:10.1001/jamanetworkopen.2020.25594.
10. Olson M. The logic of collective action: public goods and the theory of groups. Cambridge (MA): Harvard University Press; 1965.
11. Hardin G. The tragedy of the commons: the population problem has no technical solution; it requires a fundamental extension in morality. Science. 1968;162(3859):1243–8. doi:10.1126/science.162.3859.1243.
12. Stern PC, Dietz T, Ostrom E. Perspective: research on the commons: lessons for environmental resource managers. Taylor & Francis; 2002. p. 61–4.
13. Feinberg A, Ghorbani A, Herder P. Diversity and challenges of the urban commons: a comprehensive review. Int J Commons. 2021;15(1):1. doi:10.5334/ijc.1033.
14. Su Y, Yu H, Wang M, Li X, Li Y. Why did China's cost-reduction-oriented policies in food safety governance fail? The collective action dilemma perspective. Canadian J Agri Economics. 2022;70(3):203–17. doi:10.1111/cjag.12313.
15. Mesch GS, Schwirian KP. Social and political determinants of vaccine hesitancy: lessons learned from the H1N1 pandemic of 2009-2010. Am J Infect Control. 2015;43(11):1161–5. doi:10.1016/j.ajic.2015.06.031.
16. Ferrante G, Baldissera S, Moghadam PF, Carrozzi G, Trinito MO, Salmaso S. Surveillance of perceptions, knowledge, attitudes and behaviours of the Italian adult population (18–69 years) during the 2009–2010 A/H1N1 influenza pandemic. Eur J Epidemiol. 2011;26(3):211–9. doi:10.1007/s10654-011-9576-3.
17. Myers LB, Goodwin R. Determinants of adults' intention to vaccinate against pandemic swine flu. BMC Public Health. 2011;11:1–8. doi:10.1186/1471-2458-11-15.
18. Rönnerstrand B. Social capital and immunisation against the 2009 a (H1N1) pandemic in Sweden. Scand J Public Health. 2013;41(8):853–9. doi:10.1177/1403494813494975.
19. Gilles I, Bangerter A, Clémence A, Green EG, Krings F, Staerklé C, Wagner-Egger P. Trust in medical organizations predicts pandemic (H1N1) 2009 vaccination behaviour and perceived efficacy of protection measures in the Swiss public. Eur J Epidemiol. 2011;26(3):203–10. doi:10.1007/s10654-011-9577-2.
20. Hilton S, Smith E. Public views of the UK media and government reaction to the 2009 swine flu pandemic. BMC Public Health. 2010;10(1):1–0. doi:10.1186/1471-2458-10-697.
21. SteelFisher GK, Blendon RJ, Bekheit MM, Mitchell EW, Williams J, Lubell K, Peugh J, DiSogra CA. Novel pandemic a (H1N1) influenza vaccination among pregnant women: motivators and barriers. Am J Obstet Gynecol. 2011;204(6):S116–S23. doi:10.1016/j.ajog.2011.02.036.
22. Cassady D, Castaneda X, Ruelas MR, Vostrejs MM, Andrews T, Osorio L. Pandemics and vaccines: perceptions, reactions, and lessons learned from hard-to-reach latinos and the H1N1 campaign. J Health Care Poor Underserved. 2012;23(3):1106–22. doi:10.1353/hpu.2012.0086.
23. Börjesson M, Enander A. Perceptions and sociodemographic factors influencing vaccination uptake and precautionary behaviours in response to the A/H1N1 influenza in Sweden. Scand J Public Health. 2014;42(2):215–22. doi:10.1177/1403494813510790.
24. Lin L, McCloud RF, Jung M, Viswanath K. Facing a health threat in a complex information environment: a national representative survey examining American adults' behavioral responses to the 2009/2010 A(H1N1) pandemic. Health Educ Behav. 2018;45(1):77–89. doi:10.1177/1090198117708011.
25. Hilyard KM, Freimuth VS, Musa D, Kumar S, Quinn SC. The vagaries of public support for government actions in case of a pandemic. Health Aff. 2010;29(12):2294–301. doi:10.1377/hlthaff.2010.0474.
26. Charania NA, Tsuji LJS. The 2009 H1N1 pandemic response in remote first nation communities of Subarctic Ontario: barriers and improvements from a health care services perspective. Int J Circumpolar Health. 2011;70(5):564–75. doi:10.3402/ijch.v70i5.17849.
27. Hernández-Jover M, Taylor M, Holyoake P, Dhand N. Pig producers' perceptions of the influenza pandemic H1N1/09 outbreak and its effect on their biosecurity practices in Australia. Prev Vet Med. 2012;106(3–4):284–94. doi:10.1016/j.prevetmed.2012.03.008.
28. Walter D, Böhmer MM, Reiter S, Krause G, Wichmann O. Risk perception and information-seeking behaviour during the 2009/10

influenza a (H1N1) pdm09 pandemic in Germany. Eurosurveillance. 2012;17(13). doi:10.2807/ese.17.13.20131-en.
29. Boerner F, Keelan J, Winton L, Jardine C, Driedger SM. Understanding the interplay of factors informing vaccination behaviour in three Canadian provinces. Hum Vaccin Immunother. 2013;9(7):1477–84. doi:10.4161/hv.24427.
30. Babalola S. Maternal reasons for non-immunisation and partial immunisation in northern Nigeria. J Paediatr Child Health. 2011;47(5):276–81. doi:10.1111/j.1440-1754.2010.01956.x.
31. Danis K, Georgakopoulou T, Stavrou T, Laggas D, Panagiotopoulos T. Socioeconomic factors play a more important role in childhood vaccination coverage than parental perceptions: a cross-sectional study in Greece. Vaccine. 2010;28(7):1861–9. doi:10.1016/j.vaccine.2009.11.078.
32. Patel TA, Pandit NB. Why infants miss vaccination during routine immunization sessions? Study in a rural area of Anand District, Gujarat. Indian J Public Health. 2011;55(4):321–3. doi:10.4103/0019-557X.92417.
33. Mitchell S, Andersson N, Ansari NM, Omer K, Legorreta Soberanis J, Cockcroft A. Equity and vaccine uptake: a cross-sectional study of measles vaccination in Lasbela District, Pakistan. BMC Int Health Hum Rights. 2009;9(1):1–10. doi:10.1186/1472-698X-9-S1-S7.
34. Determann D, de Bekker-Grob EW, French J, Voeten HA, Richardus JH, Das E, Korfage IJ. Future pandemics and vaccination: public opinion and attitudes across three European countries. Vaccine. 2016;34(6):803–8. doi:10.1016/j.vaccine.2015.12.035.
35. Hobson-West P. Understanding vaccination resistance: moving beyond risk. Health Risk Soc. 2003;5(3):273–83. doi:10.1080/13698570310001606978.
36. Chanel O, Luchini S, Massoni S, Vergnaud JC. Impact of information on intentions to vaccinate in a potential epidemic: swine-origin influenza a (H1N1). Social Sci Med. 2011;72(2):142–8. doi:10.1016/j.socscimed.2010.11.018.
37. Irwin KL, Jalloh MF, Corker J, Mahmoud BA, Robinson SJ, Li W, Marston B, Sellu M, Jalloh MB, Diallo AA. Attitudes about vaccines to prevent Ebola virus disease in Guinea at the end of a large Ebola epidemic: results of a national household survey. Vaccine. 2017;35(49):6915–23. doi:10.1016/j.vaccine.2017.06.026.
38. Wakefield AJ, Murch SH, Anothony A, Linnell J, Casson DM, Malik M, Berelowitz M, Dhillon AP, Thomson MA, Harvey P, et al. RETRACTED: Ileal-lymphoid-nodular hyperplasia, non-specific colitis, and pervasive developmental disorder in children. Lancet. 1998;351(9103):637–41. doi:10.1016/S0140-6736(97)11096-0.
39. Gust DA, Darling N, Kennedy A, Schwartz B. Parents with doubts about vaccines: which vaccines and reasons Why. Pediatrics. 2008;122(4):718–25. doi:10.1542/peds.2007-0538.
40. Raude J, Setbon M. Lay perceptions of the pandemic influenza threat. Eur J Epidemiol. 2009;24(7):339–42. doi:10.1007/s10654-009-9351-x.
41. Balkhy HH, Abolfotouh MA, Al-Hathlool RH, Al-Jumah MA. Awareness, attitudes, and practices related to the swine influenza pandemic among the Saudi public. BMC Infect Dis. 2010;10(1):1–7. doi:10.1186/1471-2334-10-42.
42. Nyakarahuka L, Skjerve E, Nabadda D, Sitali DC, Mumba C, Mwiine FN, Lutwama JJ, Balinandi S, Shoemaker T, Kankya C. Knowledge and attitude towards Ebola and Marburg virus diseases in Uganda using quantitative and participatory epidemiology techniques. PLoS Negl Trop Dis. 2017;11(9):e0005907. doi:10.1371/journal.pntd.0005907.
43. Smailbegovic MS, Laing G, Bedford H. Why do parents decide against immunization? The effect of health beliefs and health professionals. Child Care Health Dev. 2003;29(4):303–11. doi:10.1046/j.1365-2214.2003.00347.x.
44. Poltorak M, Leach M, Fairhead J, Cassell J. 'MMR talk'and vaccination choices: an ethnographic study in brighton. Social Sci Med. 2005;61(3):709–19. doi:10.1016/j.socscimed.2004.12.014.
45. Wiysonge CS, Ndwandwe D, Ryan J, Jaca A, Batouré O, Anya BPM, Cooper S. Vaccine hesitancy in the era of COVID-19: could lessons from the past help in divining the future? Hum Vaccin Immunother. 2022;18(1):1–3. doi:10.1080/21645515.2021.1893062.
46. Webb Hooper M, Nápoles AM, Pérez-Stable EJ. No populations left behind: vaccine hesitancy and equitable diffusion of effective COVID-19 vaccines. J Gen Intern Med. 2021;36(7):2130–3. doi:10.1007/s11606-021-06698-5.
47. Freeman D, Loe BS, Chadwick A, Vaccari C, Waite F, Rosebrock L, Lambe S, Petit A, Lewandowsky S, Vanderslott S, Innocenti S. COVID-19 vaccine hesitancy in the UK: the Oxford coronavirus explanations, attitudes, and narratives survey (Oceans) II. Psychol Med. 2022;52(14):3127–41. doi:10.1017/S0033291720005188.
48. Wang J, Jing R, Lai X, Zhang H, Lyu Y, Knoll MD, Fang H. Acceptance of COVID-19 vaccination during the COVID-19 pandemic in China. Vaccines. 2020;8(3):482. doi:https://doi.org/10.3390/vaccines8030482.
49. Wang C, Han B, Zhao T, Liu H, Liu B, Chen L, Cui F, Liu J, Zheng H, Zhang S. Vaccination willingness, vaccine hesitancy, and estimated coverage at the first round of COVID-19 vaccination in China: a national cross-sectional study. Vaccine. 2021;39(21):2833–42. doi:10.1016/j.vaccine.2021.04.020.
50. Robertson E, Reeve KS, Niedzwiedz CL, Moore J, Blake M, Green M, Benzeval MJ, Benzeval MJ. Predictors of COVID-19 vaccine hesitancy in the UK household longitudinal study. Brain Behav Immun. 2021;94:41–50. doi:10.1016/j.bbi.2021.03.008.
51. Jain J, Saurabh S, Kumar P, Verma MK, Goel AD, Gupta MK, Raghav PR, Raghav PR. COVID-19 vaccine hesitancy among medical students in India. Epidemiol Infect. 2021;149:149. doi:10.1017/S0950268821001205.
52. Nguyen KH, Srivastav A, Razzaghi H, Williams W, Lindley MC, Jorgensen C, Singleton JA, Singleton JA. COVID-19 vaccination intent, perceptions, and reasons for not vaccinating among groups prioritized for early vaccination — United States, September and December 2020. Am J Transplant. 2021;21(4):1650–6. doi:10.1111/ajt.16560.
53. Mo PKH, Luo S, Wang S, Zhao J, Zhang G, Lau L, Li JT, Xie L, Lau JTF. Intention to receive the COVID-19 vaccination in China: application of the diffusion of innovations theory and the moderating role of openness to experience. Vaccines. 2021;9(2):129. doi:10.3390/vaccines9020129.
54. Earnshaw VA, Eaton LA, Kalichman SC, Brousseau NM, Hill EC, Fox AB. COVID-19 conspiracy beliefs, health behaviours, and policy support. Transl behav med. 2020;10(4):850–6. doi:10.1093/tbm/ibaa090.
55. Salali GD, Uysal MS. COVID-19 vaccine hesitancy is associated with beliefs on the origin of the novel coronavirus in the UK and Turkey. Psychol Med. 2022;52(15):3750–2. doi:10.1017/S0033291720004067.
56. Lockyer B, Islam S, Rahman A, Dickerson J, Pickett K, Sheldon T, Wright J, McEachan R, Sheard L, Bradford Institute for Health Research Covid-19 Scientific Advisory Group. Understanding COVID-19 misinformation and vaccine hesitancy in context: findings from a qualitative study involving citizens in bradford. UK Health Expect. 2021;24(4):1158–67. doi:10.1111/hex.13240.
57. Hou Z, Tong Y, Du F, Lu L, Zhao S, Yu K, Piatek SJ, Larson HJ, Lin L. Assessing COVID-19 vaccine hesitancy, confidence, and public engagement: a global social listening study. J Med Internet Res. 2021;23(6):e27632. doi:10.2196/27632.
58. Verger P, Dubé E. Restoring confidence in vaccines in the COVID-19 era. Expert Rev Vaccines. 2020;19(11):991–3. doi:10.1080/14760584.2020.1825945.
59. Okubo R, Yoshioka T, Ohfuji S, Matsuo T, Tabuchi T. COVID-19 vaccine hesitancy and its associated factors in Japan. Vaccines. 2021;9(6):662. doi:10.3390/vaccines9060662.
60. Edwards B, Biddle N, Gray M, Sollis K, Di Gennaro F. COVID-19 vaccine hesitancy and resistance: correlates in a nationally representative longitudinal survey of the Australian population. PLoS One. 2021;16(3):e0248892. doi:10.1371/journal.pone.0248892.

61. Schernhammer E, Weitzer J, Laubichler MD, Birmann BM, Bertau M, Zenk L, Caniglia G, Jäger CC, Steiner G. Correlates of COVID-19 vaccine hesitancy in Austria: trust and the government. J Public Health. 2022;44(1):e106–e16. doi:10.1093/pubmed/fdab122.
62. Freeman D, Lambe S, Yu LM, Freeman J, Chadwick A, Vaccari C, Waite F, Rosebrock L, Petit A, Vanderslott S, et al. Injection fears and COVID-19 vaccine hesitancy. Psychol Med. 2021;53 (4):1185–95. doi:10.1017/S0033291721002609.
63. Allington D, McAndrew S, Moxham-Hall V, Duffy B. Coronavirus conspiracy suspicions, general vaccine attitudes, trust and coronavirus information source as predictors of vaccine hesitancy among UK residents during the COVID-19 pandemic. Psychol Med. 2023;53(1):236–47. doi:10.1017/S0033291721001434.
64. Du F, Chantler T, Francis MR, Sun FY, Zhang X, Han K, Hou Z, Yu H, Tu S, Larson H. The determinants of vaccine hesitancy in China: a cross-sectional study following the Changchun Changsheng vaccine incident. Vaccine. 2020;38(47):7464–71. doi:10.1016/j.vaccine.2020.09.075.
65. Ebrahimi OV, Johnson MS, Ebling S, Amundsen OM, Halsøy Ø, Hoffart A, Johnson SU, Johnson SU. Risk, trust, and flawed assumptions: vaccine hesitancy during the COVID-19 pandemic. Front Public Health. 2021;9:700213. doi:10.3389/fpubh.2021.700213.
66. Qunaibi EA, Helmy M, Basheti I, Sultan I. A high rate of COVID-19 vaccine hesitancy among Arabs: results of a large-scale survey. MedRxiv. 2021-03.
67. Wright SC, Taylor DM, Moghaddam FM. Responding to membership in a disadvantaged group: from acceptance to collective protest. J Pers Soc Psychol. 1990;58(6):994. doi:10.1037/0022-3514.58.6.994.
68. Wang J, Lu X, Lai X, Lyu Y, Zhang H, Fenghuang Y, Jing R, Li L, Yu W, Fang H. The changing acceptance of COVID-19 vaccination in different epidemic phases in China: a longitudinal study. Vaccines. 2021;9(3):191. doi:10.3390/vaccines9030191.
69. Gao Z, House LA, Xie J. Online survey data quality and its implication for willingness-to-pay: a cross-country comparison. Can J Agric Econom. 2016;64(2):199–221. doi:10.1111/cjag.12069.
70. Gao Z, House L, Bi X. Impact of satisficing behaviour in online surveys on consumer preference and welfare estimates. Food Policy. 2016;64:26–36. doi:10.1016/j.foodpol.2016.09.001.
71. Jones MS, House LA, Gao Z. Respondent screening and revealed preference axioms: testing quarantining methods for enhanced data quality in web panel surveys. Public Opin Q. 2015;79 (3):687–709. doi:10.1093/poq/nfv015.
72. Soares P, Rocha JV, Moniz M, Gama A, Laires PA, Pedro AR, Dias S, Leite A, Nunes C. Factors associated with COVID-19 vaccine hesitancy. Vaccines. 2021;9(3):300. doi:10.3390/vaccines9030300.
73. Rosenbaum PR, Rubin DB. The central role of the propensity score in observational studies for causal effects. Biometrika. 1983;70 (1):41–55. doi:10.1093/biomet/70.1.41.
74. Lechner M. Earnings and employment effects of continuous gff-the-job training in east Germany after unification. J Bus Econ Stat. 1999;17(1):74–90. doi:10.1080/07350015.1999.10524798.
75. Sianesi B. An evaluation of the Swedish system of active labor market programs in the 1990s. Rev Econ Stat. 2004;86(1):133–55. doi:10.1162/003465304323023723.
76. Caliendo M, Kopeinig S. Some practical guidance for the implementation of propensity score matching. J Econ Surv. 2008;22 (1):31–72. doi:10.1111/j.1467-6419.2007.00527.x.
77. Olson M. The logic of collective action: public goods and the theory of groups. Social Forces; 1973.
78. Dye C, Mills MC. COVID-19 vaccination passports. Science. 2021;371(6535):1184–1184. doi:10.1126/science.abi5245.
79. Oliu-Barton M, Pradelski BSR, Woloszko N, Guetta-Jeanrenaud L, Aghion P, Artus P, Fontanet A, Martin P, Wolff GB. The effect of COVID certificates on vaccine uptake, health outcomes, and the economy. Nat Commun. 2022;13(1):3942. doi:10.1038/s41467-022-31394-1.
80. Jarrett C, Wilson R, O'Leary M, Eckersberger E, Larson HJ, SAGE Working Group on Vaccine Hesitancy. Strategies for addressing vaccine hesitancy - A systematic review. Vaccine. 2015;33 (34):4180–90. doi:10.1016/j.vaccine.2015.04.040.
81. Fu LY, Bonhomme LA, Cooper SC, Joseph JG, Zimet GD. Educational interventions to increase HPV vaccination acceptance: a systematic review. Vaccine. 2014;32(17):1901–20. doi:10.1016/j.vaccine.2014.01.091.
82. Ward K, Chow MYK, King C, Leask J. Strategies to improve vaccination uptake in Australia, a systematic review of types and effectiveness. Aust N Z J Public Health. 2012;36(4):369–77. doi:10.1111/j.1753-6405.2012.00897.x.
83. Cairns G, Macdonald L, Angus K, Walker L, Cairns-Haylor T, Bowdler T. Systematic literature review of the evidence for effective national immunisation schedule promotional communications. J R Stat Soc. 2012;167(4):613–26. doi:10.1111/j.1467-985X.2004.aeI2.x.
84. Chen L, Li Z, Lu X, Deng Y, Lu K, Li T, Lu L, Wang Z, Lu J. Changes in COVID-19 vaccine hesitancy at different times among residents in Guangzhou, China. Front Public Health. 2023;11:1164475. doi:10.3389/fpubh.2023.1164475.
85. Walkowiak MP, Domaradzki J, Walkowiak D. Better late than never: predictors of delayed COVID-19 vaccine uptake in Poland. Vaccines (Basel). 2022;10(4):528. doi:10.3390/vaccines10040528.
86. Ostrom E. Governing the commons: the evolution of institutions for collective action. Cambridge: Cambridge University Press; 1990.
87. Ostrom E. A diagnostic approach for going beyond panaceas. Proc Natl Acad Sci USA. 2007;104(39):15181–7. doi:10.1073/pnas.0702288104.

Appendix A. Online Participant Consent Form

Title: COVID-19 vaccination intention survey

Declaration by Participant

- I have read the Participant Information Sheet or someone has read it to me in a language that I understand.
- I understand the purposes, procedures and risks of the research described in the project.
- I have had an opportunity to ask questions and I am satisfied with the answers I have received.
- I freely agree to participate in this research project as described and understand that I am free to withdraw at any time during the project without affecting my future care or *my relationship* with *the researchers.*
- I understand that I will be given a signed copy of this document to keep.

Declaration by Person performing the informed consent discussion

- I have given a verbal explanation of the research project; its procedures and risks and I believe that the participant has understood that explanation.

Feel free to choose the following options according to your actual situation

- I willing to start the Q&A
- I refuse to participant in the Q&A

Appendix B. The statistical principles of propensity score matching

From a statistical perspective, let the dependent variable values for members of the experimental and control groups be represented by Y_1 and Y_0, respectively, and let w be a binary variable where $w = 1$ represents individuals in the experimental group and $w = 0$ represents individuals in the control group. Therefore, when an individual belongs to the experimental group, the value of $E(Y_1|w = 1)$ is observable as a factual event, while the value of $E(Y_0|w = 1)$ is a counterfactual event that cannot be observed. For instance, the impact of university education on an individual who has received it cannot be observed under a hypothetical scenario where he had not received university education. Similarly, for the control group, the value of $E(Y_0|w = 0)$ is observable as a factual event, while the value of $E(Y_1|w = 0)$ is counterfactual and therefore unobservable. Thus, our objective is to determine the causal relationship between the differences in "fact" and "counterfactual" elements among individuals in the experimental group, which can be calculated as a weighted average.

$$T = \pi[E(Y_1|w = 1) - E(Y_0|w = 1)] + (1 - \pi)[E(Y_1|w = 0) - E(Y_0|w = 0)] \tag{A.(1)}$$

The symbol π signifies the proportion of all individuals surveyed who belong to the experimental group.

Since counterfactuals are unobservable and the same group of people can only belong to either the experimental or control group, it is imperative to fulfill the following non-confounding assumption when making causal inferences:

$$E(Y_1|w = 0) = E(Y_1|w = 1)$$

$$E(Y_0|w = 0) = E(Y_0|w = 1)$$

The notion here is that a separate group of individuals in the control group can act as a representative for the counterfactual state of individuals in the experimental group. Therefore, it is possible to simplify Equation (1) as follows:

$$T = E(Y_1|w = 1) - E(Y_0|w = 0)$$

In the context of a randomized experiment, the assumptions presented in equations $E(Y_1|w = 0) = E(Y_1|w = 1)$ and $E(Y_0|w = 0) = E(Y_0|w = 1)$ hold, since experimental individuals are assigned to the experimental and control groups in a random manner. However, it is worth noting that when relying on observational data, the fact of randomization cannot be guaranteed. Thus, it becomes imperative to control for confounding variables as much as possible to maintain the independence between variable w and variables Y_1 and Y_0, i.e.,

$$E(Y_1|w = 0, x) = E(Y_1|w = 1, x)$$

$$E(Y_0|w = 0, x) = E(Y_0|w = 1, x)$$

The variable x represents a confounding variable. As long as the confounding variable can be identified and controlled, w can be approximated to be independent of Y_1 and Y_0 (Rosenbaum and Rubin, 1983), i.e.,

$$(Y_0, Y_1) \perp w|x$$

At this stage, a specific propensity score P for the confounding variable x is obtained through logistic regression, leading to the following relationship:

$$E(Y_1|w = 0, P) = E(Y_1|w = 1, P)$$

$$E(Y_0|w = 0, P) = E(Y_0|w = 1, P)$$

In summary, it is possible to obtain an "approximate" fulfillment of the non-confounding assumption, thereby obtaining the desired causal inference.